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13. ABSTRACT *(Maximum 200 words)*
SCENARIO-J is a Java®-based thermoregulatory prediction model developed by Kraning and Gonzalez of USARIEM. The model was previously evaluated under thermally stressful laboratory environments and the model performance in long-term field conditions was still unclear. This study evaluates the reliabilities of SCENARIO_J in long-term military field training and showed the comparisons in these results with previous laboratory controlled validation studies.
Environmental, anthropometric, physiological, and geo-location data were collected for 4 Marine Corps males, who participated in a one-week infantry training exercise at Quantico, VA. The statistical analyses of root mean square deviation (RMSD) and correlation coefficient (r), which focused on 6-hour period training assault exercise on an enemy position, were utilized to compare the observed and predicted values for both heart rate (HR) and core temperature (Tcr).
SCENARIO_J predictions often began its calculations using unrepresentative Tcr and need to be corrected. The high RMSD for both HR and Tcr occurred due to lack of sensitivity to dynamic changes in physical activity and possibly with psychological strain. The r-values and prediction error distributions were varied by individuals, suggesting a larger sample size was required. More importantly, the quality of the input data to estimate metabolic rate was necessary.

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SCENARIO_J, validation, combat training, heart rate, core temperature, energy expenditure

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CHARACTERIZATION OF UNCERTAINTIES IN A THERMAL STRAIN PREDICTION MODEL FOR MILITARY APPLICATIONS

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The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46.

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EXECUTIVE SUMMARY

SCENARIO_J is a dynamic human thermoregulatory simulation model developed by Kraning and Gonzalez of the U.S. Army Research Institute of Environmental Medicine (USARIEM) and written in the Java® program language. The model predicts thermo-physiologic responses of individuals due to their physical characteristics, activities, clothing, and the environment. The predictions include core (T_{cr}) and skin temperatures, blood flows, heart rate (HR), shivering, sweat rates, dehydration status, and other parameters. Also, the metabolic energy produced for various activities can be estimated from the individual's speed of movement, terrain and grade traversed and load carried.

SCENARIO_J is warfighter oriented to estimate physiological status and aid in prediction of thermal injuries. The model provides longitudinal predictions of human physiological responses to controlled laboratory environments and activities.

The objectives of this study were to 1) evaluate the accuracy of SCENARIO_J in predicting soldiers' thermoregulatory responses in long-term field operations; 2) quantify sensitivity of the model to inherent uncertainties in the input data streams; 3) identify the error characteristics of predicted variables; and 4) review reported accuracy of earlier versions of SCENARIO tested in laboratory studies.

Environmental and individual anthropometric data, as well as time series physiological and geo-location data, were obtained for 4 Marine Corps males (age: 25 ± 2 [SD] yr; ht: 182 ± 4 cm; wt: 76.5 ± 3.5 kg; body fat: 14.3 ± 3.9%), who participated in a 1-week infantry training exercise at Quantico, VA. Measured values of HR by a continuous electrocardiogram and T_{cr} by a swallowed radio pill were recorded during a 6-hour period training assault exercise on an enemy position, and were compared to SCENARIO_J predicted values. The deviations between measured and predicted variables across the time period were analyzed with Root Mean Square Deviations (RMSD).

Differences between predicted and measured values for both HR and T_{cr} were greater than those in previous laboratory heat-related studies (8, 9). SCENARIO_J consistently under-predicted the observed internal body temperatures in the beginning of simulations. SCENARIO_J predictions consistently began its calculations using unrepresentative starting body temperatures. The problem of unrepresentative initial model core temperatures needs to be corrected for individual variation. In addition, the model predicted HR better during non-fighting activities than in the time of the drastic changes observed during fighting activities. However, correcting HR modeling for sudden and/or emotional activities is less obvious as currently the model uses only blood flow calculated from aerobic metabolic activity to predict HR.

Importantly, sensitivity of the model to speed of movement, terrain, grade, and load was not substantial. Because the model requires these elements to estimate metabolic rates, the limitations in quantifying these values in a field setting caused

inaccuracies in the predicted thermo-physical responses. Improvements in the input data streams are important for accurate assessment of model predictions.

INTRODUCTION

Thermoregulatory prediction models are increasingly needed for accurate physiological status and risk assessment to prevent heat and cold injuries among deployed soldiers. These biophysical prediction models can provide consistent and repeatable simulations over a wide range of working and environmental conditions to assess physiological risks because they are rationally based on thermodynamics and heat transfer coupled with active physiological control systems and biophysical properties. In contrast, a statistical regression prediction model (8) is limited to the test conditions used in its development.

However, it is important to evaluate model predictions of physiological responses in real field situations for its acceptance and useful application. Recent improvements in physiological data collection methods, physiological sensors and communication devices have facilitated the military field evaluation process. Comparisons of physiological data with model predictions provide the analytical basis needed to identify uncertainties and characterize model performance.

SCENARIO, a thermoregulatory biophysical prediction model developed by Kraning and Gonzalez (11), focuses primarily on warfighter applications. It operates as a time-series numerical simulation of thermoregulatory responses based on metabolic energy, cardiovascular and sweating responses and heat flow. The thermo-physiology of the warfighter is modeled as six compartments representing core, muscle, fat, central blood, inner vascular skin, and outer non-vascular skin (11). It predicts heart rate (HR) and core temperature (T_{cr}) of individuals as a function of *a*) metabolic heat production associated with work activity (grade, speed of movement, terrain); *b*) anthropometry (height, weight, % body fat); *c*) weather (air temperature, relative humidity, solar radiation, wind speed); and *d*) clothing characteristics (thermal insulation, vapor permeability). The model was primarily validated with datasets collected from short-term laboratory experiments (8, 9). For instance, when subjects wearing battle dress uniforms (BDU) and/or heavy protective clothing ensembles walked on the treadmills (3% grade) at a constant speed (1.34 ms^{-1}) under warm environment (30°C; 25% relative humidity) for 70 minutes, SCENARIO predictions of T_{cr} agreed reasonably well with measured T_{cr} except during the first 10 minutes (8). When subjects wearing shorts engaged in 50-minute bouts of intermittent exercise under hot and dry environmental conditions (49°C, 20% relative humidity), the model predictions tended to over-predict T_{cr}, although within a satisfactory range (±1 standard deviation) (8). In comparison to other thermoregulatory predictions models such as USARIEM Heat Strain Model and the John B. Pierce Laboratory Two-Node Thermoregulatory Model, SCENARIO performed well for various laboratory conditions and activities (8).

In this study, SCENARIO_J, an updated Java® -based version (v0.61) of the original SCENARIO model, was used to simulate individuals during a 6-hour segment of a military field training exercise involving intermittent activities. The purposes of the study were to *a*) evaluate the fidelity of the SCENARIO_J model in predicting soldiers' responses in long-duration field operations; *b*) quantify the model's output sensitivity to

inherent uncertainties in the input data streams; *c*) identify the error distribution characteristics of predicted variables; and *d*) review the reported accuracy of earlier versions of SCENARIO in laboratory settings.

MATERIALS AND METHODS

SUBJECTS

The subjects for this analysis were part of a larger USARIEM study of U.S. Marine Corps (USMC) volunteers participating in infantry field training at Quantico, VA, 8-15 September 1999 (2). A sub-set of 4 subjects was selected after reviewing data availability during the training segment of interest (18:00 to 23:59 hours EST on 8 September 1999). The test volunteers gave their informed consent to participate in the testing in accordance with US Army Regulation 70-25 regarding the use of volunteers as subjects of research.

FIELD PROCEDURES

The USMC training involved both physical and mental exercises in tactics, combat, and the use of weapons and communications within a platoon. Subjects wore the battle dress uniform (BDU), personal armor systems for ground troops (PASGT) helmet and vest during the exercises, and carried various weapons and equipment based on their assignments. The subjects reported their primary hourly activities using activity log books.

DATA COLLECTION

Physiological Measurements

Heart Rate and Core Temperature. Heart rate (HR) and core temperature (T_{cr}) of these subjects were monitored every minute. A chest-strap sensor (Vantage XL model, Polar Electro, Ft. Washington, NY) was used to measure and record HR while T_{cr} was measured with an ingested telemetry pill (2.2 cm x 1.0 cm; Human Technologies Inc., St. Petersberg, FL) and a Body Core Temperature Monitor Receiver (Fitsense, Inc., Wellesley, MA).

Environmental Measurements

Air temperature (T_a), dew point (T_{dp}), and wind speed (WS) were recorded every 15 minutes by a portable weather station (Model CR 10, Campbell Scientific, Logan, UT). Hourly solar radiation (SR) was an estimate based on U.S. Naval Observatory data (14) and a database of SR measurements (Matthew, unpublished, 1998) during 18:00-23:59 on 8 September 1999. In this way, average solar radiation was estimated as 0 W/m^2 during 20:00-23:59 hours and 100 W/m^{2}during 18:00-19:59 hours.

Movement Activity

Global Positioning Systems (GPS) (Trimble Lassen SK8 GP receiver, Trimble, Inc., Sunnyvale, CA) were used to record subjects' locations (longitude, latitude) every minute. The data were used to calculate subjects' movements including speed and distance, which is used to estimate metabolic energy expenditure.

Metabolic Rates

The energy expenditure was calculated every minute using the Pandolf et al., equation (13):

$$M = 1.5W + 2.0(W+L)(L/W)^2 + \eta(W+L)[1.5V^2 + 0.35VG]$$

where M = metabolic rate (watts); W = subject body weight (kg); L = weight of load carried (kg); V = speed of walking (ms^{-1}); G = grade (%); and η = terrain factor.

Speed was calculated from the distance moved, estimated from GPS data, during 60 seconds. Terrain factor and grade were used as constant values of 1.2 and 0%, respectively, consistent with the topographical information for the training site obtained from the Quantico Military Installation Map (4).

DATA ANALYSIS

Modeling analysis focused on the 6-hour period from 18:00-23:59 local time on 8 September, 1999, that encompassed a training exercise consisting of an assault on an enemy position. Modeling input data elements (i.e., energy expenditure, and weather) were calculated by 15-minute averages for each of the 24 consecutive time blocks comprised in the 6-hour period. The 15-minute "epoch" intervals used for input condition updates were intended to provide a statistical smoothing of generally "noisy" data that frequently had missing 1-minute values for critical geo-location information. When there were no data available for a 15-minute epoch, such were generated by averaging metabolic costs between prior and subsequent epochs for that point. Each epoch was labeled at the midpoint of the 15-minute duration: for instance, 18:08 represents the mean metabolic cost during 18:00-18:14, and 19:38 stands for the average metabolic cost between 19:30-19:44. SCENARIO predictions were also averaged in the same manner to allow comparative analyses.

The correlations and differences between physiological predictions and observed measures were compared based on the estimate of product-moment correlation coefficient (r) and Root Mean Square Deviation (RMSD) across 6-hour periods in each individual. The r, which identifies overall directional associations between predicted and observed measurements of the pairs, was calculated as (1):

$$r = \frac{N\sum XY - (\sum X)(\sum Y)}{\sqrt{[N\sum X^2 - (\sum X)^2][N\sum Y^2 - (\sum Y)^2]}}$$

where X = predicted value at each epoch; Y = observed measure at each epoch; and N = number of pairs of scores.

The RMSD was calculated as follows (7):

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

where d_i = difference between observed and predicted at each epoch; and n = the number of compared points. The RMSD was used to quantify the average difference between predicted and observed measurements across time (7).

RESULTS

SUBJECTS' CHARACTERISTICS

The age, physical characteristics, and resting metabolic rates (RMR) for the 4 test volunteers are shown in Table 1.

Table 1. Age and physical characteristics of test volunteers

Subject	Age (yr)	Height (cm)	Nude weight (kg)	Body fat (%)	RMR (watts)
1	25	180	75.0	14.9	85
2	24	186	81.8	17.6	89
3	23	178	74.6	16.2	84
4	27	183	74.6	8.7	89
Mean	25	182	76.5	14.3	87
SD	2	4	3.5	3.9	2.8

RMR = Resting Metabolic Rate = watts = ((370+21.6*FFM)/1440)/0.0143, where FFM (Fat Free Mass in kg) = nude wt – [nude wt x % body fat]) (3).

ACTIVITY

Table 2 is the summary of hourly primary activity of each subject during 18:00-23:00 hours on 8 September. Activity codes were not defined prior to the training, and subjects wrote hourly activities in their open notebooks. The activity log was later summarized as common activities (2). For instance, subject number 1 (SN1) was defending (defense) during 18:00-18:59 hours, while SN2 and SN4 were preparing for attacks during 18:00-19:59 hours. "Live fire" involves actual firing, while "fire watch" represents watching firing. In addition, these activity codes may not always completely represent physiological status or correspond to loaded weights, because subjects might have engaged in activities other than the primary activity during any 1-hour period.

Table 2. Activity summary

Local Time	SN1	SN2	SN3	SN4
18:00	Defense	Preparation	Battle	Preparation
19:00	Attack	Camouflage	Attack	Preparation
20:00	Attack	Attack	Attack	Attack
21:00	Fire watch	Attack	Fire watch	Attack
22:00	Debrief	Live fire	Debrief	Attack
23:00	Marching to different sites	Eat	Marching to different sites	Attack

SN = Subject Number

LOAD CARRIAGE

Hourly estimates of load weights were calculated from daily fully dressed weights of subjects (without weapons or protective equipment) and their hourly equipment log. For instance, the fully dressed weight of SN2, whose semi-nude weight was 81.8 kg, was 109.9 kg on 8 September. The equipment log during 18:00 hours indicated an M-203 attachment (1.05 kg), squad automatic weapon (7.05 kg), PASGT vest (4.09 kg), and PASGT helmet (1.50 kg). First, the total loaded weight during this hour was calculated as 123.6 kg (= 109.9 + 13.7 kg) by adding the fully dressed weight and equipment weights (13.7 = 1.05 + 7.05 + 4.09 + 1.50 kg) from the equipment log. Then, the load carried was estimated by subtracting semi-nude weight from the total loaded weight during 1 hour (41.8 kg = 123.6 – 81.8). Table 3 is the summary of hourly loads carried by each individual. Load carriage varied based on soldiers' duties.

Table 3. Load carriage summary

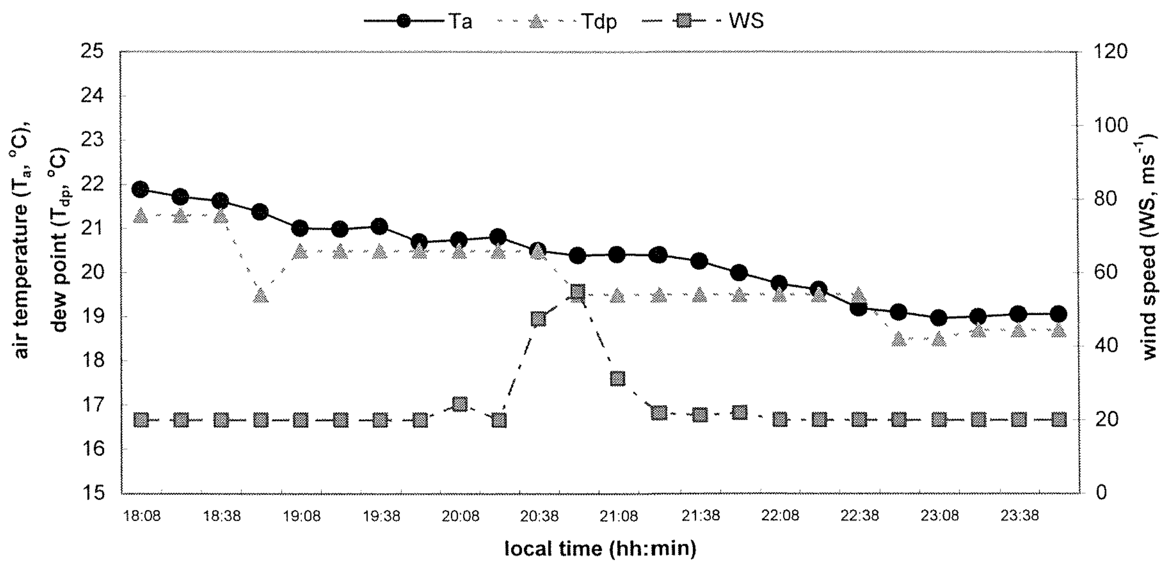
Local Time	SN1	SN2	SN3	SN4
18:00	35.7	41.8	36.3	15.4
19:00	35.7	41.8	36.3	15.4
20:00	35.7	41.8	43.8	15.4
21:00	35.7	41.8	36.3	15.4
22:00	35.7	41.8	36.3	15.4
23:00	35.7	34.7	51.2	15.4

Unit: kg
SN = Subject Number

WEATHER

Figure 1 is the weather summary for the experimental period. Means for air temperature (T_a) and wind speed (WS) were 20.3 ± 0.9 [SD]°C and 0.2 ± 0.1 m•s^{-1}, respectively. The mean dew point (T_{dp}) was 20 ± 1°C. The graph shows that though the environment's air temperature was not high, it was very humid during the 6-hour training period.

Figure 1. The weather summary for the 6-hour study period on 8 September

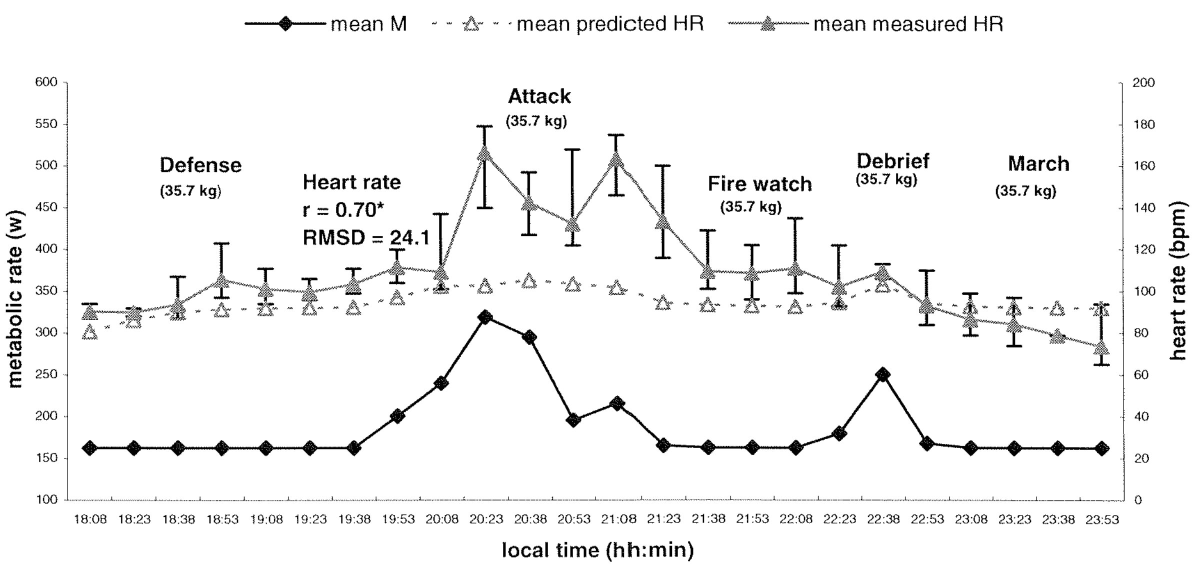


PHYSIOLOGICAL SUMMARY BY SUBJECT

Subject 1 (SN1)

Figure 2 shows the comparisons between 15-minute averaged predicted and measured HR and the 15-minute averaged metabolic costs (M) during 18:00-23:00 hours. The vertical bars indicate highest and lowest HR measured in each 15-minute epoch. It is seen that variabilities of M corresponded to variabilities in measured HR during attack periods. The r and RMSD between predicted and measured HR during the 6-hour period were 0.70 ($p < 0.05$) and 24.1 bpm, respectively. When SN1 was engaged in marching to different sites, debriefing, fire watch and defense activities, HR predictions were close to the measured rates. However, when observed HR drastically changed during attack periods, the model underestimated the measured HR despite increased M.

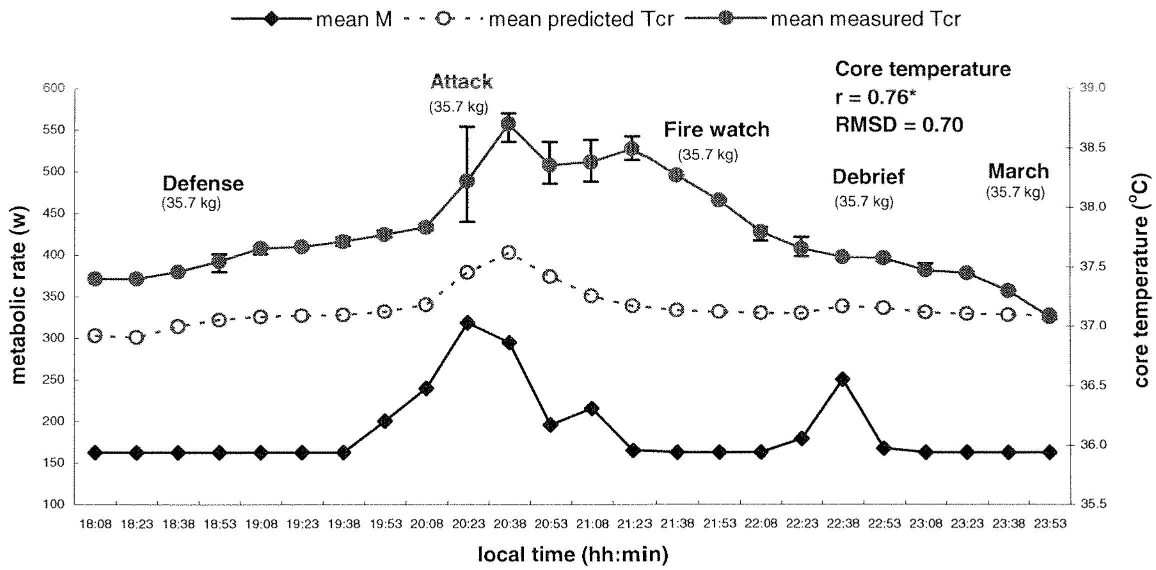
Figure 2. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured heart rates (HR) for SN1



(kg) indicates load weights.
Note: Vertical bars represent highest and lowest HR in each 15-minute epoch.
* indicates statistical significance at $p = 0.05$.

Figure 3 shows the average M in every 15-minute period and the comparisons between measured and predicted T_{cr} for SN1. The vertical bars indicate highest and lowest actual T_{cr} recorded in each 15-minute epoch. The r and RMSD for T_{cr} were 0.76 ($p < 0.05$) and 0.70°C, respectively. The model predicted a lower initial T_{cr} than the measured values, and this offset persisted during the rest of the experiment period. Similar to HR, the errors in predicted T_{cr} became larger during the attack period.

Figure 3. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured core temperatures (T_{cr}) for SN1

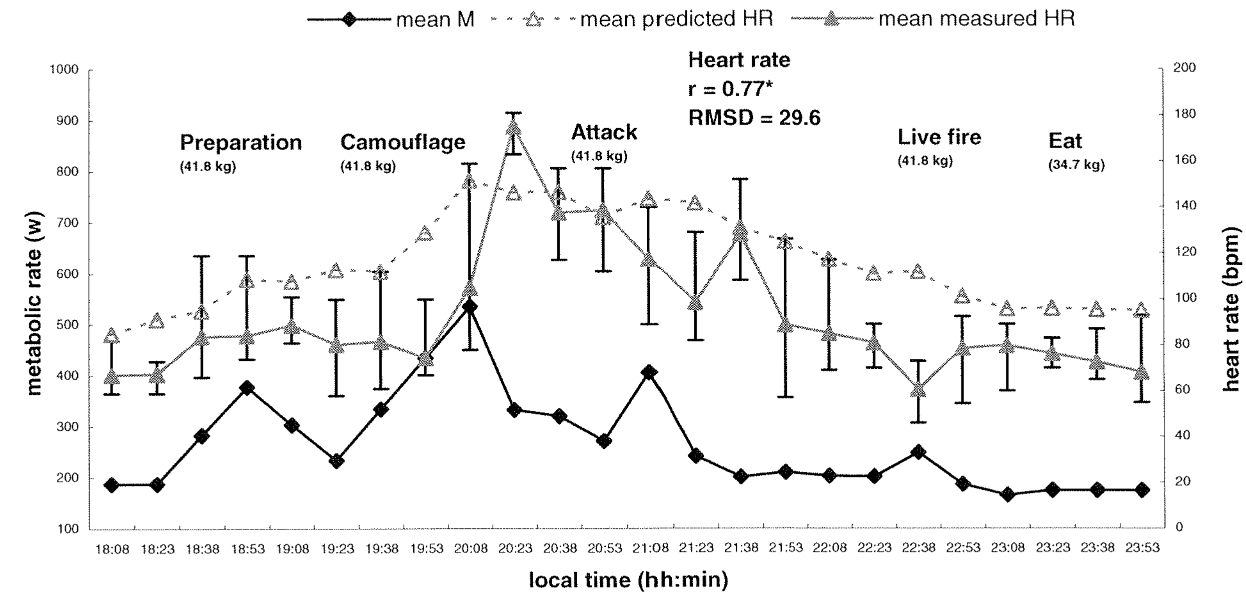


(kg) indicates load weights.
Vertical bars represent highest and lowest T_{cr} in each 15-minute epoch.
* indicates statistical significance at p = 0.05.

Subject 2 (SN2)

Figure 4 shows the average M in every 15-minute period, as well as the predicted and measured HR for SN2 during the 6 hours. Similar to SN1, greater variabilities of M were observed in attack periods. The M gradually increased while the subject was preparing for fighting (preparation, camouflage) and the predicted and measured HR followed. The r and RMSD for HR were 0.77 ($p < 0.05$) and 29.6 bpm, respectively. SCENARIO_J consistently predicted higher HR than observed measures except for the 20:23 epoch period. Interestingly, the prediction errors for HR tended to be higher in this individual except during attack periods.

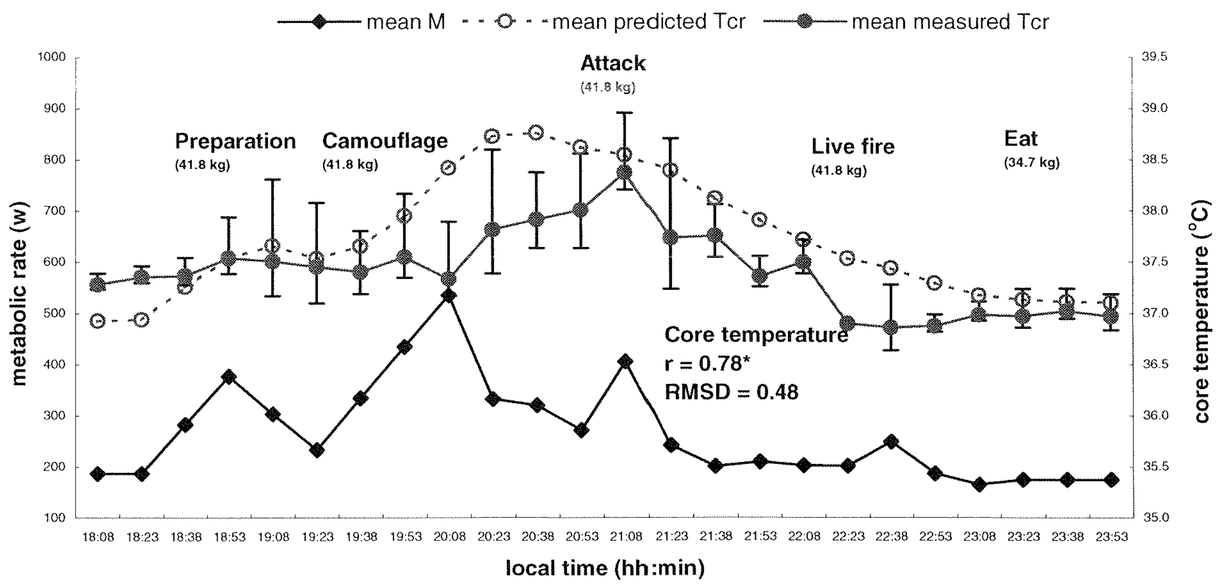
Figure 4. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured heart rates (HR) for SN2



(kg) indicates load weights.
Vertical bars represent highest and lowest HR in each 15-minute epoch.
* indicates statistical significance at p = 0.05.

Figure 5 shows the average M in every 15-minute period and the comparisons between predicted and measured T_{cr} for SN2. The vertical bars indicate highest and lowest T_{cr} measured in each 15-minute epoch. The r and RMSD for T_{cr} were 0.78 ($p < 0.05$) and 0.48°C, respectively. Although T_{cr} predictions were higher than observed values across time except for the beginning, the model predictions, overall, were close to measured T_{cr}.

Figure 5. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured core temperatures (T_{cr}) for SN2

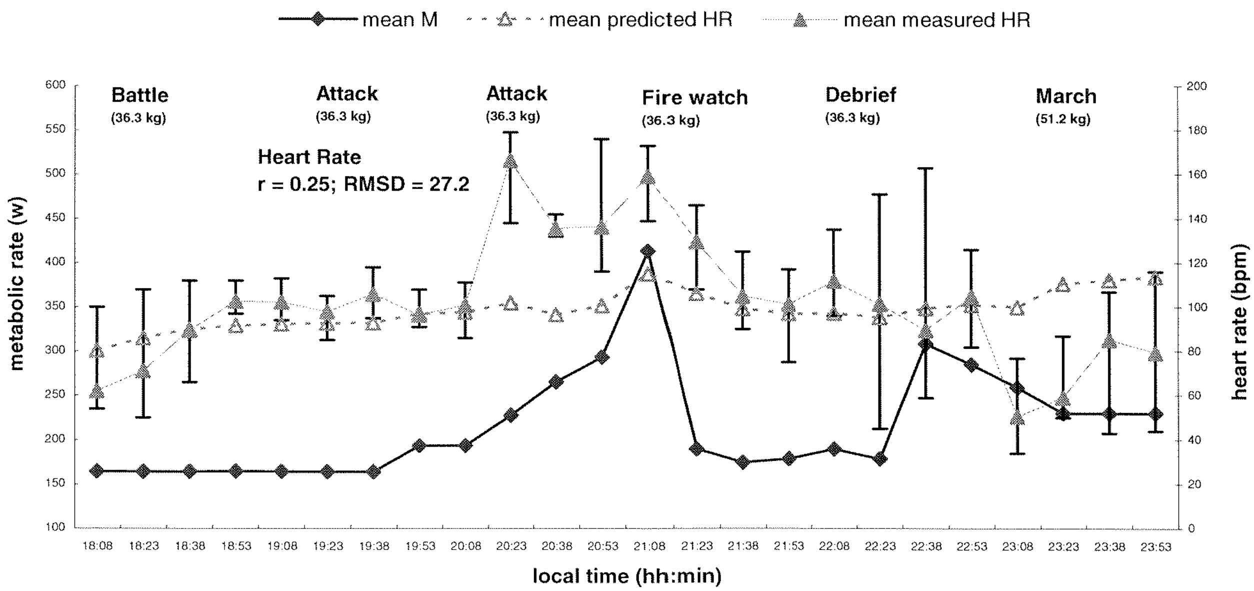


(kg) indicates load weights.
Vertical bars represent highest and lowest T_{cr} in each 15-minute epoch.
* indicates statistical significance at $p = 0.05$.

Subject 3 (SN3)

The summary of the predicted and measured HR of SN3 in each 15-minute epoch, as well as the mean M is shown in Figure 6. The metabolic costs gradually increased during attack activity and reached a peak around the beginning of 21:00 hours. Marching to different sites and carrying a 51.2 kg load required this individual to spend more metabolic energy than that of SN1 carrying 35.7 kg during marching. The RMSD and r for HR was 27.2 bpm and 0.25 ($p > 0.05$), respectively. Although the model predicted well when activities were not strenuous and HR was steady around 100 bpm, it could not predict the measured rapid HR changes shown in attack periods. Although the RMSDs for HR of this individual were not qualitatively different from the rest of the subjects, the predicted and measured variables showed a lack of linearity with a low correlation.

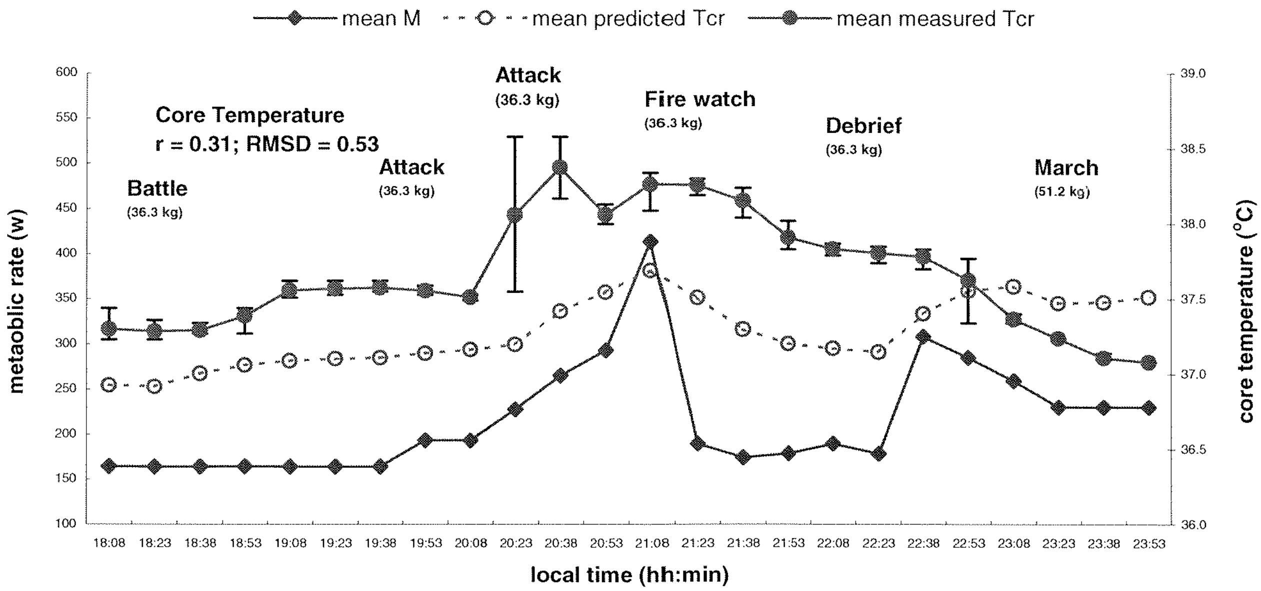
Figure 6. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured heart rates (HR) for SN3



(kg) indicates load weights.
Vertical bars represent highest and lowest HR in each 15-minute epoch.

Figure 7 shows the mean M in every 15-minute period, and the comparison between mean predicted and measured T_{cr} for SN3. The RMSD and r for T_{cr} were 0.53°C and 0.31 ($p > 0.05$), respectively. T_{cr} predictions paralleled measured values, but tended to be lower. The prediction errors for T_{cr} were greater after the periods associated with attacks. Although the RMSDs for HR and T_{cr} of this individual were not qualitatively different from the rest of the subjects, the low r indicated that the predicted and measured variables showed a lack of linear associations.

Figure 7. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured core temperatures (T_{cr}) for SN3

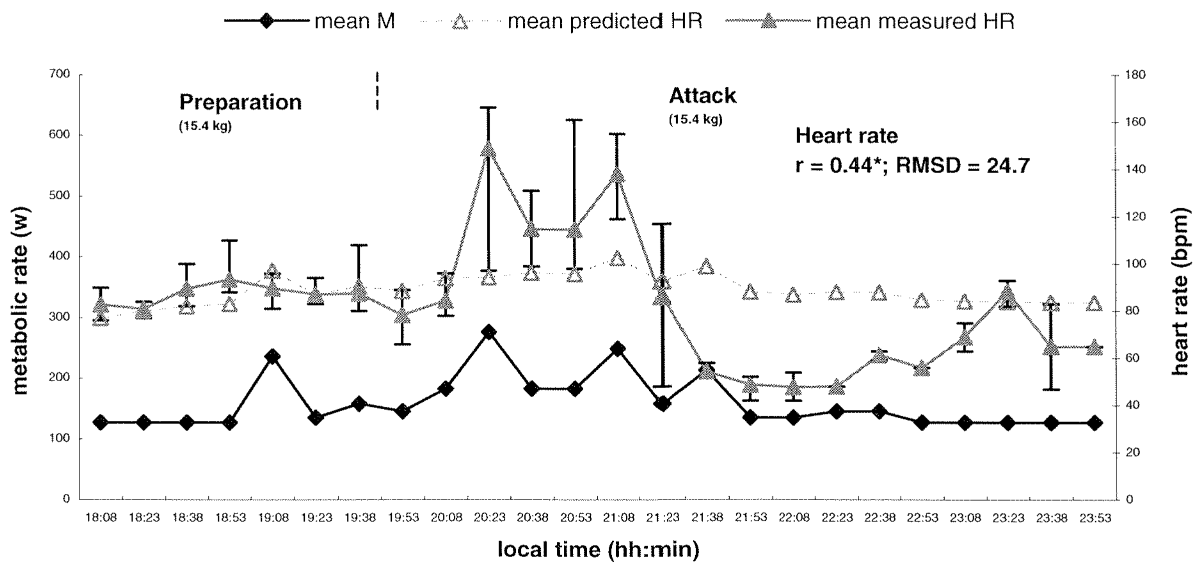


(kg) indicates load weights.
Vertical bars represent highest and lowest T_{cr} in each 15-minute epoch.

Subject 4 (SN4)

Figure 8 shows the comparisons between predicted and measured HR, in addition to the summary of M during the 6-hour period. The subject's M had peaks during attack activities that generally corresponded with the measured HR peaks. The RMSD and r for HR were 24.7 bpm and 0.44 ($p < 0.05$), respectively. The model predicted HR well in the beginning when measured HR and estimated M were near resting levels. But the HR predictions during the attack activities did not show the rapid elevated HR fluctuations that were measured.

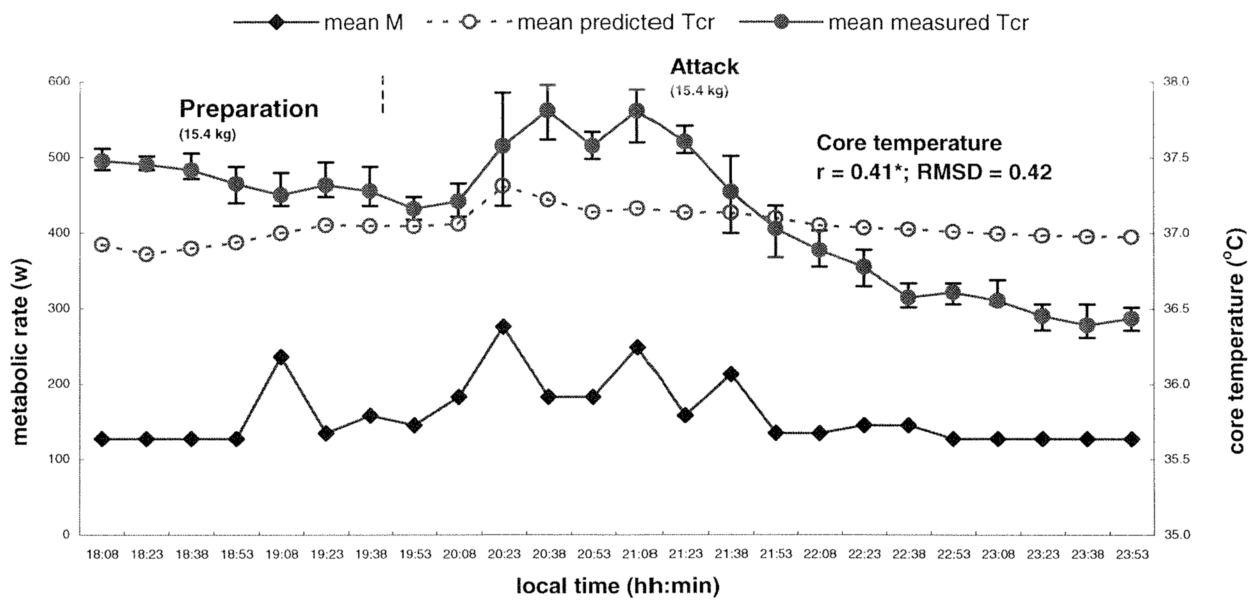
Figure 8. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured heart rate (HR) for SN4



(kg) indicates load weights.
Vertical bars represent highest and lowest HR in each 15-minute epoch.
* indicates statistical significance at p = 0.05.

Figure 9 shows the summary of 15-minute M values and the comparisons between mean predicted and measured T_{cr} for SN4. The RMSD and r for T_{cr} were 0.42°C and 0.41 ($p < 0.05$), respectively. The predicted T_{cr} was lower than the measured T_{cr} in the beginning and remained at approximately 37°C throughout the period while the measured T_{cr} reached values near 37.8 °C during the attack and fell to about 36.4° near its end.

Figure 9. The summary of mean metabolic rates (M) and comparisons between mean predicted and measured core temperatures (T_{cr}) for SN4



(kg) indicates load weights.
Vertical bars represent highest and lowest T_{cr} in each 15-minute epoch.
* indicates statistical significance at $p = 0.05$.

PREDICTION ERRORS

Heart Rate

Table 4 shows a summary of RMSDs for the predicted HR from this field study and from 5 different laboratory study datasets used by Kraning (8) to evaluate earlier versions of the SCENARIO model. The mean RMSD of this field study was ±26 bpm, which is greater than those of the laboratory studies. As previously shown, greater deviations in this field study were associated with periods when measured HR was rapidly elevated.

Table 4. The summary comparisons of the SCENARIO model RMSDs for heart rates and study conditions in 6 different studies

Data	N	Clothing	Activity (watts)	Duration (min)	Environment (Ta, RH)	RMSD (bpm)	Type of study
Kraning & Gonzalez (10)	4	Shorts	380*	75	30°C, 25%	±7	Laboratory
Kraning & Gonzalez (10)	4	BDU + BDO	380*	75	30°C, 25%	±9	Laboratory
Pandolf et al. (12)	10	Shorts	360*	60	49°C, 20%	±19	Laboratory
Gonzalez et al. (5)	5	Shorts	324-366	40	28°C-45°C, 30%-80%	±6	Laboratory
Gonzalez et al. (6)	14	CPO	465-481	90	35°C, 50%	N/A	Laboratory
This study	4	BDU + BA	128-538	360	19°C-22°C, 91%-98%	±26	Field

* indicates average metabolic cost.

BDU = battle dress uniform; BA = body armor (PASGT vest and helmet); BDO= battledress overgarment; CPO = chemical protective overgarment.

Note: Except for this study, RMSDs were estimated by Kraning (8).

Figure 10 is the overall distribution of HR error (difference = predicted – measured HR) during the 6-hour periods among all subjects (N = 24 epochs x 4). The mean error is only 3.3 bpm; however, a wide dispersion of positive and negative errors was observed (SD = 26.4). The errors that occurred most frequently were in the magnitude between –5 and +10 bpm, and also those around + 20 bpm.

Figure 10. The error count distribution of heart rates (HR)

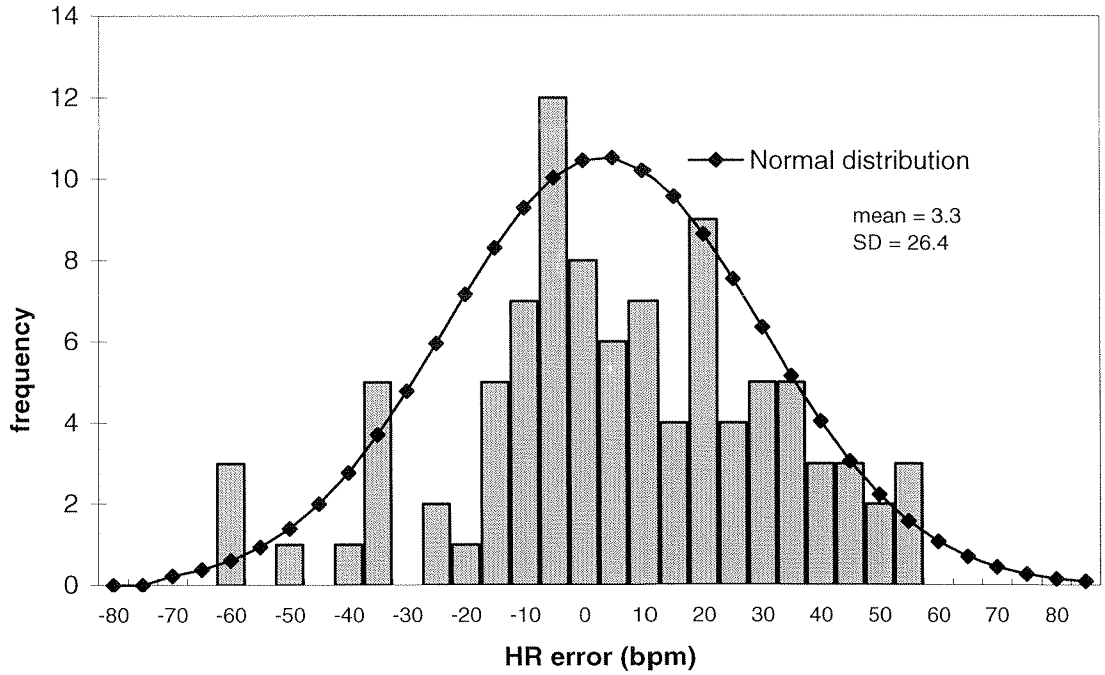
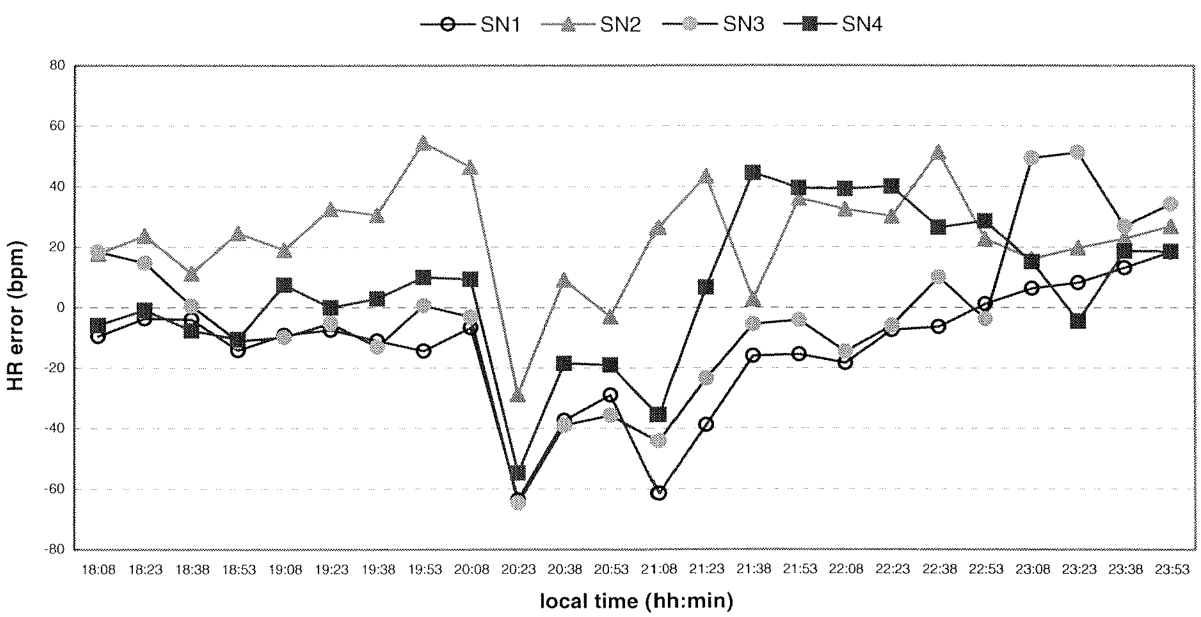


Figure 11 shows the summary of HR error (predicted – measured) of subjects across the time period. For subjects 2 and 4, predictions tended to overestimate their HR as compared to subjects 1 and 3, and contributed to the skewed error frequency distribution shown in Figure 10. However, consistent underestimated HR predictions were observed among all subjects between 20:23 and 21:23 hours when they were attacking and their heart rates reached peaks. When subjects were engaged in less strenuous activities such as preparing for the attack around 18:00-19:00 hours (except for SN2) and debriefing around 22:00 hours (SN1, SN3), the predictions were fairly close to the observed HR.

Figure 11. The error (predicted – measured) distributions for heart rates (HR) by subjects



Core Temperature

Table 5 shows the summary of the RMSD for T_{cr} of this field study and also for T_{cr} of the 5 different laboratory datasets used by Kraning (8). Similar to HR, the differences between predictions and measured values in this field study were also greater than those in the laboratory datasets.

Table 5. The summary comparisons of the SCENARIO model RMSDs for core temperatures and study conditions in 6 different studies

Data	N	Clothing	Activity (watts)	Duration (min)	Environment (Ta, RH)	RMSD (°C)	Type of study
Kraning & Gonzalez (10)	4	Shorts	380*	75	30°C, 25%	±0.19	Laboratory
Kraning & Gonzalez (10)	4	BDU + BDO	380*	75	30°C, 25%	±0.27	Laboratory
Pandolf et al. (12)	10	Shorts	360*	60	49°C, 20%	±0.27	Laboratory
Gonzalez et al. (5)	5	Shorts	324-366	40	28°C-45°C, 30%-80%	±0.17	Laboratory
Gonzalez et al. (6)	14	CPO	465-481	90	35°C, 50%	±0.21	Laboratory
This study	4	BDU + BA	128-538	360	19°C-22°C, 91%-98%	±0.53	Field

* indicates average metabolic cost.
BDU = battledress uniform; BA = body armor (PASGT vest and helmet); BDO = battle dress overgarment; CPO = chemical protective overgarment.
Note: Except for this study, RMSDs were estimated in Kraning (8).

The T_{cr} error (predicted – measured) distribution is summarized in Figure 12. The mean of the errors is -0.2 ± 0.51 [SD]°C. However, the distribution was almost bi-modal with frequency peaks at error magnitudes around -0.4°C and between 0.2°C and 0.6°C. This bi-modal distribution was partially due to the small sample size, in which error counts were repeatedly observed among the 4 individuals during the 6 hours.

Figure 12. The error count distribution of core temperatures (T_{cr})

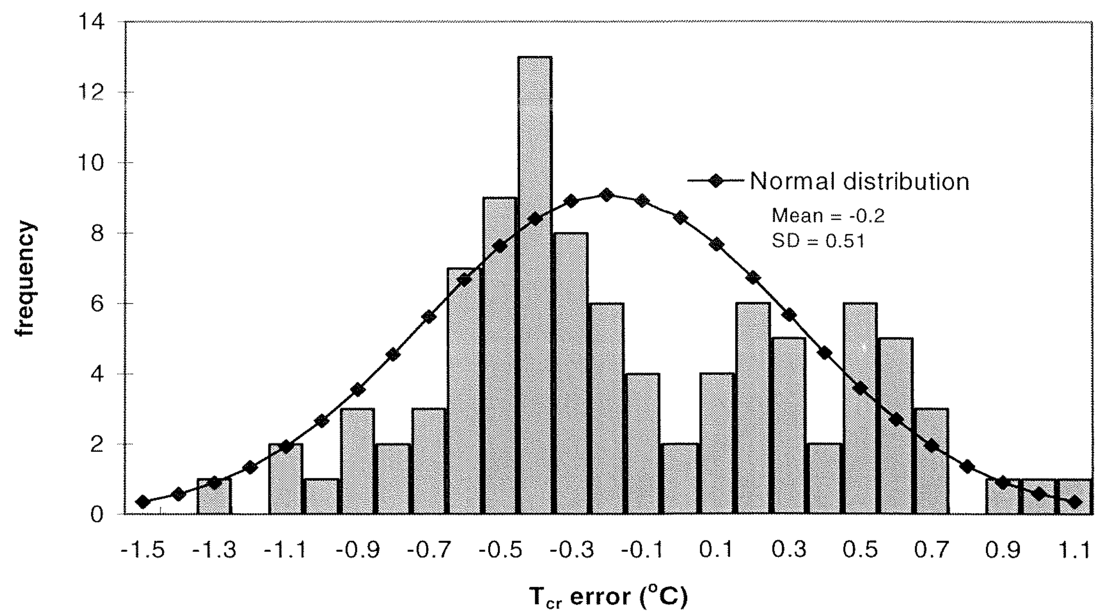
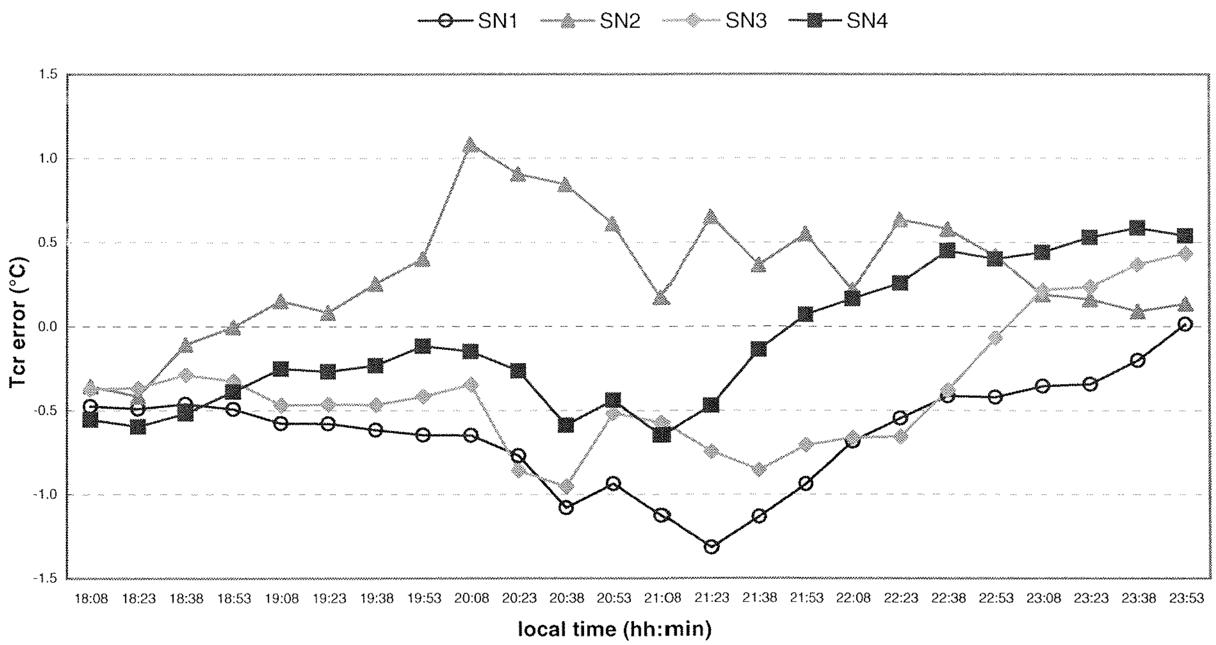


Figure 13 shows the distribution of the T_{cr} (predicted - measured) differences of each subject. Except for SN2, T_{cr} predictions tended to underestimate T_{cr} in the beginning of the 6-hour period. Similar to the HR differences of Figure 11, the differences peaked when subjects were involved in attacking activities, although SN2 showed the opposite trend.

Figure 13. The error (predicted – measured) distributions for core temperatures (T_{cr}) by subjects



DISCUSSION

Although subjects were engaged in sporadic activities in this field study, the following common characteristics were observed among individuals. SCENARIO_J predicted HR and T_{cr} reasonably well when both were in the resting condition (70 bpm, 37°C) or during a gradual change (±15 bpm, ±0.3°C). However, the model tended to predict lower T_{cr} in the early epochs because the model's currently fixed "initialization" of body core temperature at 37°C was not always representative of the initial body temperatures of these subjects. Ideally, the model's initial T_{cr} value should have been set to subjects' measured body temperatures. In addition, model predictions greatly deviated from measured values when other factors induced rapid HR fluctuations, such as occurred during the fighting activities of this field study.

Prediction errors of the model were greater in this field study than in controlled laboratory studies (8, 10). The average RMSD among the subjects during the 6-hour experiment were ±26 bpm for HR, and ±0.53°C for T_{cr}. This study was not able to show consistent error patterns of the model across the time due to individual variabilities derived from the small sample size. Error distributions for both HR and T_{cr}, were bi-modal, reflecting the high RMSDs, and suggest a larger sample size (N>4) is required to quantify significant error patterns of the model. In addition, prediction errors were different by activities and subjects: the differences between measured and predicted values were high when subjects were engaged to fighting activities. The initial measured T_{cr} and HR values, which were different for each subject in this case, caused prediction errors due to the initial fixed values in the model for HR and Tcr of 70 bpm and 37°C, respectively. Such individual variabilities were also observed in the measures of correlations (r), ranging from 0.25 to 0.77 for HR, and 0.31 to 0.78 for T_{cr}. Although the pooled r between predicted and measured values among the individuals was significant at the p-value of 0.05 for both HR (r =0.38) and T_{cr} (r = 0.35), the variation (r^2) in the predicted variables was poorly explained by measured variables.

Model sensitivity to potential input errors was also a significant concern in this study. Although a key assumption regarding local terrain factor (1.2) and grade (0%) for each epoch was applied, uncertainty in the reliability of information, including activity, terrain factors, speed of movement, loaded weights, grades, and missing values could have dramatically altered the model output results over the long hours of training. For instance, terrain factors and grades, which are essential to compute metabolic rates for inputs, may not have been constant if subjects were fighting in wide areas of the training site. Assuming 5% or 10% grades instead of 0% for SN2 increased maximum predicted T_{cr} by 1.0 and 1.75°C, respectively, and maximum predicted heart increased by 50 and 60 bpm, respectively (Matthew, unpublished, 2002). Furthermore, the current SCENARIO_J version (v0.61) does not have capabilities for operating with missing values, which were often present in this field study. Thus, averaging the available inputs before and after a missing value was used to compensate for missing values. Although a 15-minute summary of metabolic rate for input data may have been adequate to predict most thermal responses for gradual activity changes, HR

predictions were poor, particularly during fighting periods. Such predictions possibly occurred due to *a*) an unsystematic activity log reported by subjects; *b*) inaccurate metabolic rate calculations from the GPS device; *c*) inadequate length for input data (15-minute epoch) to predict the significant thermal responses; *d*) insufficient substitution of missing values; *e*) drastically increased HR not triggered by metabolic rate or thermal stress but other elements such as psychologically induced stressors; and *f*) the lack of heat acclimatization effects, which were important for model analyses. Thus, the limitations imposed by the field setting caused unavoidable uncertainties in these input data elements. The current model assumes HR is solely dependent on the blood flow for aerobic metabolic heat production, work and thermal regulation (8). However, integrated elements such as e) and f) above in this study are additional factors that affect the model, and need to be carefully considered when interpreting SCENARIO_J predictions for warfighter situations.

In conclusion, military field trainings are important to learn warfighters' responses to operational and environmental training conditions that are close to real battlefield conditions. The datasets collected in such field trainings are essential in identifying model characteristics that may not have been proven in laboratory studies. This study examined questions of the model's behaviors raised in previous laboratory studies (8): e.g. responses to different military tasks assigned during long-term periods. In this study, test volunteers were randomly assigned to different activities at different time periods. However, the study design led to some ambiguity in the elements required for the model's input, reduced the sample size for analysis, and together contributed to the model's failure to consistently predict the measured responses. Thus, accurate input data and increased sample size are extremely important to assess the model's behavior. Developing devices for collecting real-time measurements or videotaping of soldiers activities during the long-hours of training may be helpful to accurately document information of the warfighter's movements, the topography, and even an estimation of missing physiological values. Finally, this field study showed that adjustments for starting physiological model status, estimates of missing values, and predictions during strenuous activities associated with psychological stressors, are important factors to be addressed in future prediction models.

CONCLUSIONS

1. The model is sensitive to uncertainties in the input elements that are used to determine metabolic expenditure. These include: speed of movement, load, and terrain characteristics, as well as substitutions of missing values.
2. The under-prediction of T_{cr} commonly observed in the early epochs was likely due to the model's currently fixed value starting at 37°C.
3. The mean summary of metabolic rates during a 15-minute epoch length for input data may be adequate to predict thermal responses when metabolic rates were less variable.
4. SCENARIO_J predicted better in conditions during gradual changes of actual HR and T_{cr} than in abrupt changes in warfighter activities, particularly those observed during fighting mode.
5. SCENARIO_J has previously been shown to accurately predict certain thermoregulatory responses to laboratory thermal environment. This field study shows that, with the suggested input and model code adjustments, SCENARIO_J can be a useful predictor of human thermal responses to the dynamic activities and environments of the warfighter.

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